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Rice responses to changes in floodwater and N timing in southern USA☆

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Abstract

Delayed application and/or early draining of floodwater to lowland irrigated rice (*Oryza sativa* L.) should allow producers in southern USA more time for ground application of chemicals while reducing potential hazards from aerial applications and conserving water. Two field studies were conducted to evaluate growth and yield responses of "Tebonnet", "Alan", and "Texmont" rice to reduced flood duration and altered N management. Depending upon the study, treatments consisted of normal (four- to five-leaf stage) or delayed timing of flood application in combination with recommended or earlier-than-recommended draining of the floodwater, and full-season flush irrigation. Nitrogen was either applied once at the four- to five-leaf stage or as a three-way split with normal- or earlier-than-recommended timing. Flush irrigation reduced shoot and root growth and yield of rice as compared to normal flood while delayed-flood irrigation reduced shoot dry weight but had no effect on root length density or grain and head-rice yields. Nitrogen uptake was greater with a single preflood application of N than with a three-way split application. Yields were not affected by N management or earlier-than-recommended draining of the floodwater. These data indicate that the duration of floodwater application currently practiced in rice production in southern USA may be reduced without sacrificing grain yield or quality. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Irrigation management; Water deficit stress; Root length density

1. Introduction

Although rice is grown world-wide under upland and lowland environments, flooding generally produces larger yields than saturated or aerobic conditions (Satyanarayana and Ghildyal, 1970). There appears to be agreement among the international community that a critical time for the presence of flood water for optimum grain yield and grain quality of rice is during reproductive development (De Datta, 1981). Tanaka et al. (1963) found that direct-seeded rice flooded at early reproductive growth yielded 10% less grain than rice grown with a flood beginning at early tillering. Tanaka et al. (1964) suggested, how-

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ever, that yields of delayed flooded rice should not differ from rice flooded throughout the season as long as soil water content during the nonflooded period does not stress the plant nor enhance nitrification/denitrification losses of N. Lilley and Fukai (1994) found that water deficit imposed during vegetative growth did not reduce yields while water stress during reproductive growth resulted in 20–70% less grain yield than well-irrigated rice.

In USA, rice is grown in the presence of a flood throughout all or most of its development (Bollich et al., 1994). However, water management alternatives such as reducing the duration of flood water application must be developed for rice producers in southern USA which may be required to conserve water in regions where aquifers are being depleted or to reduce aerial applications of chemicals because of the associated health hazards. Studies on lowland irrigated rice in southern USA have shown that grain yields may not be reduced when flood is delayed from the four- to five-leaf stage until just prior to or at initiation of reproductive growth (McCauley and Turner, 1979; Beyrouty et al., 1992; Norman et al., 1992). In other studies, grain yield and quality were not effected when the flood was terminated as early as 2 weeks following heading (Counce et al., 1990; Dingkuhn and Le Gal, 1996), nearly 2 weeks earlier than normal at these sites.

Changes in flood water timing and duration may also necessitate changes in N fertilizer timing. Lower grain yields of rice subjected to intermittent flooding are partially due to loss of N through denitrification during alternate flooding and drying cycles (Tanaka et al., 1964; Wells and Shockley, 1978). Norman et al. (1992) showed that rice grain yields were not reduced when the flood and preflood N applications were delayed for up to 21 days past the four- to five-leaf stage. However, Castillo et al. (1992) reported that the most effective timing of N application for rice subjected to water deficit before flowering was the same as for continuously flooded rice. Similar results were reported by Hefner and Tracy (1991) for flooded and furrow-irrigated rice.

It seems likely that the duration of the essential period for flooding rice in southern USA is shorter than is currently utilized. The question remains open, however, as the effects of the combination of delayed flooding and early draining on rice growth and yield have not been examined. An understanding of whole-plant response and cultivar differences with reductions in water inputs and associated changes in N timing are fundamental to developing strategies that refine and possibly reduce the duration of water application. Thus, we evaluated the effects of delayed flood application, early flood removal, and altered N management on shoot and root growth and yield of lowland irrigated rice under the conditions of southern USA. Two field experiments were conducted to study whole-plant response of one cultivar and shoot growth and yield response of three cultivars to alternative water and N management.

2. Materials and methods

2.1. Whole-plant response (experiment 1)

"Tebonnet", a tall, early-maturing (117 days), long-grain cultivar was grown on a Crowley silt loam (very fine, montmorillinitic, thermic, Typic Albaqualfs; USDA taxonomy) at the Rice Research and Extension Center near Stuttgart, Arkansas, USA (90°50′W, 34°30′N, 70 m a.s.l.). The crops were drill seeded on 1 June 1989 and 16 May 1990 in 18-row plots (nine rows for destructive sampling and nine rows for final grain yield) measuring 4.6 m long with rows spaced 0.18 m apart. Water management treatments in 1989 were: (1) "normal flood"; application of a 5–10 cm deep flood initiated at the four- to five-leaf stage (4/5 LS) of growth, the standard water management in much of southern USA; (2) "delayed flood"; application of a 5–10 cm deep flood initiated at panicle differentiation (PD), preceded by flush irrigation whenever soil water potential fell from -0.03 to -0.05 MPa as measured with tensiometers at 0.1 m soil depth; and (3) "flush irrigation" whenever soil water potential fell from -0.03 to -0.05 MPa during the period from emergence until 30 days after heading. Following PD, flush irrigations were applied twice weekly to treatment 3 and terminated 30 days after heading. Treatments 1 and 2 were drained at the locally recommended time of 30 days after heading (Cooperative Extension Service, 1996).

Urea was applied as recommended by the University of Arkansas Cooperative Extension Service with 67 kg N ha^{-1} broadcast at the 4/5 LS, and

33 kg N ha^{-1} broadcast at both PD and PD+10 days. For treatment 1 (normal flood), the N applied at the 4/5 LS was broadcast onto the dry soil surface and flooded while N applications at PD and PD+10 days were applied into the floodwater. For treatment 3 (flush irrigation), N fertilizer at all stages was applied to the dry soil surface, followed by brief flooding for 2–4 h to incorporate the N below the soil surface. A combination of these techniques was used for treatment 2 (delayed flood) when appropriate.

Two treatments were added in 1990, one of which (treatment 4, delayed flood with early–midseason N) was in response to an apparent 10% yield reduction with delayed flooding in 1989. Treatment 4 was similar to treatment 2 except that the second and third N applications were applied at PD−10 days and PD. Treatment 5 (normal flood, early drain) was similar to treatment 1 except that the flood was removed 14 days after heading.

Butachlor (N-(butoxymethyl)-2-chloro-2′6′-diethylacteanilide) and propanil (3′,4′-dichloropropionanilide) were applied post-emergent at rates of 2.5 and 3.4 kg ai ha^{-1}, respectively, to control weeds.

2.2. Cultivar response (experiment 2)

“Alan” (tall, early-maturing (115 days), long grain), “Texmont” (semidwarf, early-maturing (116 days), long grain), and Tebonnet, were drill-seeded on a Crowley silt loam at the Rice Research and Extension Center near Stuttgart, on 15 May 1991 and 17 June 1992 in 9-row plots measuring 4.6 m long, with 0.18 m row spacing. Water management treatments were: (1) “normal flood, recommended drain”; (2) “delayed flood, recommended drain”; (3) “normal flood, early drain”; and (4) “delayed flood, early drain”. Nitrogen treatments were: (1) 50% of the N applied at the 4/5 LS and 50% split between PD and PD+10 days (recommended midseason N); (2) 50% of the N applied at the 4/5 LS and 50% split between PD−10 days and PD, (early–midseason N); and (3) all N applied at the 4/5 LS (single). Nitrogen fertilizer was applied as described in the whole-plant study.

To control weeds, thiobencarb (S-[(4-chlorophenyl)methyl]diethylcarbamothioate) and propanil were applied postemergence at the rates of 2.25 and 3.4 kg ai ha^{-1}, respectively. Bensulfuron ((2-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]methyl]benzoic acid) was also applied at 0.6 kg ai ha^{-1}.

2.3. Plant measurements

Shoot and root growth were measured at stages corresponding to active tillering, maximum tillering, panicle initiation, booting, heading, anthesis, milk stage, and harvest (physiological maturity). Root growth was measured in experiment 1 using the minirhizotron technique. Root images were obtained by inserting a micro video camera into two rectangular plexiglass tubes placed at a 45° angle within rows in each plot as described by Beyrouty et al. (1988). Roots growing along the uppermost two sides of each tube were video recorded to a depth of 0.40 m. The recordings were traced with a linear probe and root length and root length density were calculated for 0.1 m depth increments. Leaf area index (LAI) was measured in experiment 1 and shoot dry weight was measured in both experiments. Randomly selected 0.5 m sections of row were destructively sampled and leaf areas were measured with a leaf area meter. Shoot tissue (leaves, stems, and panicles) was dried at 60°C in a forced-air oven and dry weights measured. In 1991, tissue obtained at panicle initiation and heading and in 1992 at maximum tillering, panicle initiation, booting, heading, and milk stage was ground, wet ashed, and analyzed for total N using steam distillation and titration (Bremner and Mulvaney, 1982). Grain yields, determined by hand harvesting the five center rows in each nine-row yield plot in experiment 1 and the four middle rows of each plot in experiment 2 are reported at 12% moisture. In 1990, head-rice yields were calculated from unbroken kernels (Counce et al., 1990).

2.4. Experimental design

The design of experiment 1 was a split plot with water and N management combinations as the whole-plot factor in a randomized complete-block structure with four replications. Growth stage was the split-plot factor. Because of the addition of two treatments in 1990, each year was analyzed separately. The design of experiment 2 was a split–split plot with water management as the whole-plot factor in a randomized complete-block structure with four replications. Cultivar was the split-plot factor and N timing was the split–split-plot factor. Data were subjected to analysis of variance and mean separations were conducted using an LSD, where appropriate.

3. Results and discussion

The experiments were conducted to evaluate the impact of a shorter period of flooding on rice growth and yield under the cultural conditions of southern USA. In general, the present practice there is to flood at the 4/5 LS and drain at about 30 days following heading resulting in ≈85 flood days for the cultivars employed in our studies. In these studies, delaying flood application until panicle differentiation saved ≈20 flood days and early draining saved ≈16 flood days. Thus, in experiment 2, where we imposed the combination of delayed flooding and early draining, there were about 36 fewer days of flooding than under normal flooded conditions. However, the flood was present during reproductive development when rice is most sensitive to the effects of water deficit.

Flush-irrigated rice produced poorly in this study. The intent of this treatment was to grow rice under an irrigation regime similar to that of an upland crop such as soybean (*Glycine max* L.). Thus, water was applied when the soil water content was at approximately the upper limit as measured with tensiometers. Compared to normally flooded rice, LAI at booting and anthesis (Fig. 1), and shoot dry weight (Fig. 2) and RLD (Fig. 3) from booting to harvest of flush-irrigated rice were markedly less resulting in a 58 and 12% reduction in grain and head-rice yields, respectively (Table 1). The decrease in yields can be partially attributed to reduction of LAI levels (Fig. 1) below those needed (between 5 and 6 $m^2\ m^{-2}$) for maximum photosynthesis (Yoshida, 1981). Values of LAI for flush-irrigated

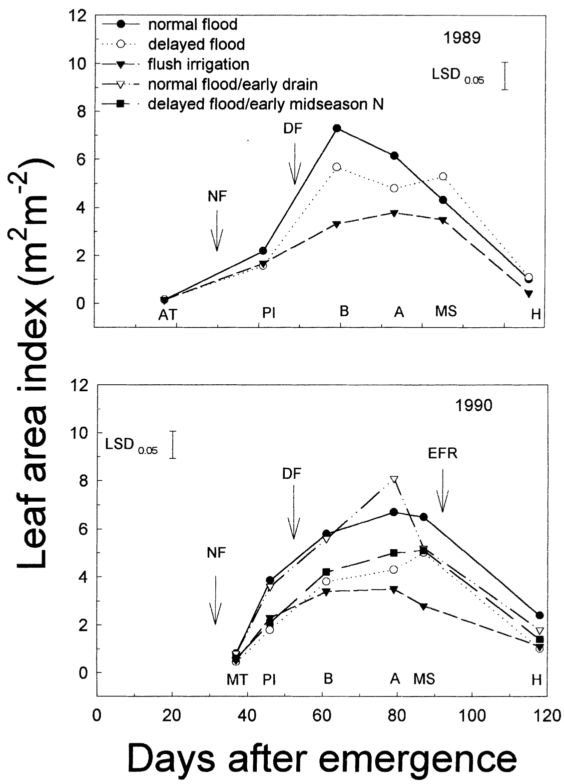

Fig. 1. Leaf area index as affected by water and N management in 1989 and 1990, experiment 1. NF=application of normal flood; DF=application of delayed flood; EFR=time of early flood removal. For stages of development AT=active tillering; MT=maximum tillering; PI=panicle initiation; B=booting; A=anthesis; MS=milk stage; H=harvest (physiological maturity). LSD (0.05) values are for comparisons within and among treatments.

Table 1
Grain and head-rice yields as affected by water and N management in 1989 and 1990, experiment 1

Treatment	Grain yield (kg ha^{-1})		Head-rice yield in 1990 (%)
	1989	1990	
Normal flood	6120	6990	59.6
Delayed flood	5520	6760	61.8
Delayed flood, early–midseason N[a]	–	7020	61.0
Normal flood, early flood removal[a]	–	7162	58.4
Flush irrigation	2840	2670	52.2
LSD (0.05)	910	680	2.6

[a] Evaluated in 1990 only.

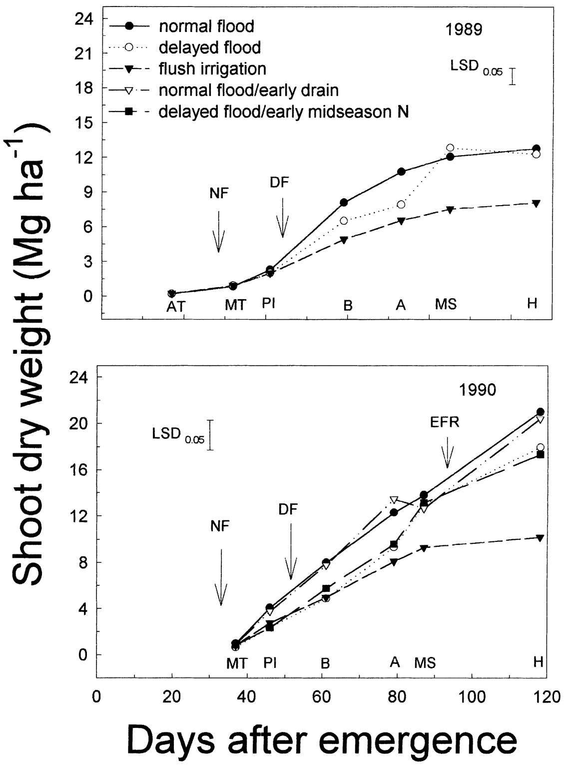

Fig. 2. Shoot dry weight as affected by water and N management in 1989 and 1990, experiment 1. NF=application of normal flood; DF=application of delayed flood; EFR=time of early flood removal. For stages of development AT=active tillering; MT=maximum tillering; PI=panicle initiation; B=booting; A=anthesis; MS=milk stage; H=harvest (physiological maturity). LSD (0.05) values are for comparisons within and among treatments.

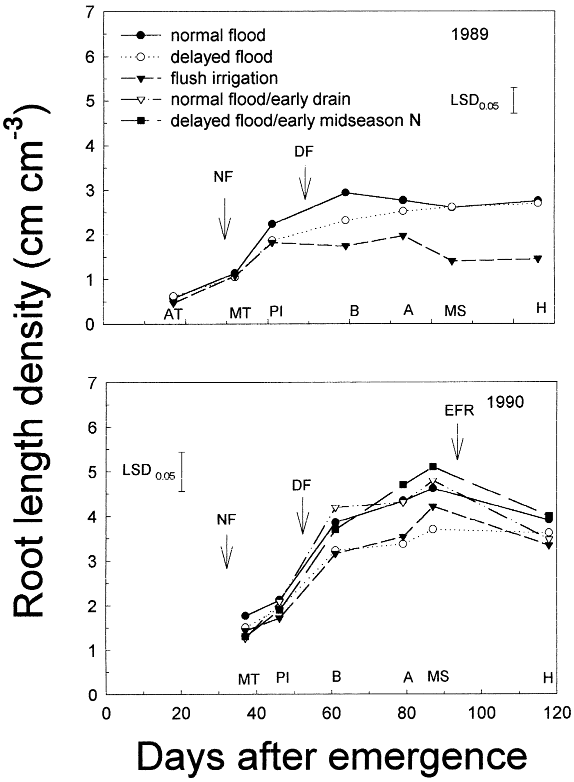

Fig. 3. Root length density (averaged across depths) as affected by water and N management in 1989 and 1990, experiment 1. NF=application of normal flood; DF=application of delayed flood; EFR=time of early flood removal. For stages of development AT=active tillering; MT=maximum tillering; PI=panicle initiation; B=booting; A=anthesis; MS=milk stage; H=harvest (physiological maturity). LSD (0.05) values are for comparisons within and among treatments.

rice did not exceed 3.8 $m^2\ m^{-2}$ and consequently adequate levels of photosynthesis may not have been achieved for maximum growth and yield.

Nitrogen uptake was 30–40% less for flush-irrigated rice at booting than for normally flooded rice (Beyrouty et al., 1994). Reduced N uptake from flush irrigation could be the result of a combination of a smaller root system and N losses from denitrification as a result of alternate wetting and drying (Wells and Shockley, 1978). Borrell et al. (1997) found that over the full-season, rice (Lemont cv) flush-irrigated in northern Australia yielded less than rice subjected to a permanent flood beginning at the three-leaf stage. McCauley (1990) measured a 20% yield reduction for 12 cultivars grown in Texas and subjected to full-season sprinkler irrigation as compared to flood irrigation. Others also have found greater grain yields and productivity from flooded rice than from rice grown under saturated or drier conditions (Satyanarayana and Ghildyal, 1970; Obermueller and Mikkelsen, 1974; Castillo et al., 1992). It is possible that changes in N application timing or rates might reduce N losses and enhance yields of flush-irrigated rice.

Aboveground biomass of rice subjected to delayed flood was generally reduced compared to normally flooded rice. LAI in experiment 1 (Fig. 1) and shoot dry weight (Fig. 2, experiment 1) in both experiments were reduced by booting or anthesis in response to delaying the flood. The increase in shoot dry weight of delayed-flooded rice by milk stage appears to be a delayed response to the late application of the flood. Shoot dry weight of rice subjected to delayed flood, early–midseason N was the same for delayed flood, recommended N, showing no benefit from early N application. Reductions in shoot dry weight in response to delayed floodwater application were 20% for Alan and Tebonnet and 24% for Texmont and were not affected by year, growth stage, early draining of floodwater, or N management.

Root length density was apparently not as sensitive to the delayed flood as was shoot growth since it was not significantly reduced as compared to normally flooded rice (Fig. 3). Beyrouty et al. (1992) also found that RLD of delayed flooded and normal flooded rice did not differ. Maximum root length of rice has been shown to occur at panicle initiation or booting (Beyrouty et al., 1988; Slaton et al., 1990). This was also true in the present study regardless of treatment. The only treatment effect on RLD was found between the two delayed flood treatments in experiment 1. Delayed flood with early–midseason N had 40% greater RLD than delayed flood and recommended N at anthesis and milk stage. This increase in RLD appears to be a response to the earlier application of N, offsetting the effects of delayed flood by enhancing root growth between panicle initiation and booting.

Although shoot growth was affected by delayed flood application, grain and head-rice yields were not. Differences in grain yields were not found between normal and delayed-flooded rice by Beyrouty et al. (1992) and McCauley and Turner (1979). Early–midseason N application and early draining in the present study did not effect grain and head-rice yields (Tables 1 and 2); these results support similar findings by Counce et al. (1990) and Dingkuhn and Le Gal (1996). Norman et al. (1992) measured a 12% reduction in total dry matter of Lemont subjected to 14 and 21 days delayed floods without a corresponding reduction in yield. In the present work, an acceptable head-rice yield of 58% or above (Cooperative Extension Service, 1996) was measured for all treatments except flush-irrigated rice. In experiment 2, when compared within a cultivar, time of flood water application and draining and N timing had no effect on yields.

In 1989, there was a trend for reduced shoot dry weight and RLD of delayed-flooded rice at booting and anthesis, although values were comparable to normally flooded rice by milk stage. There was an associated trend for a 10% reduction in grain yield of 600 kg ha^{-1} for delayed-flooded rice. It was observed that the second and third application of N in 1989 was made after the reduction in dry matter and RLD had occurred. Thus, it was hypothesized that the two midseason applications of N might be made 10 days earlier than normal to prevent this apparent reduction in plant growth and stimulate yields. In 1990, a shoot dry weight response to the early–midseason N was not observed, but with delayed flood, early–midseason N had greater RLD than rice subjected to normal midseason N (Fig. 3).

A single application of N at the 4/5 LS resulted in greater N uptake by delayed and normally flooded rice than did midseason N applications (Beyrouty et al., 1994). Maximum uptake of N applied at the 4/5 LS to rice occurs 3 weeks after application (Wilson et al., 1989; Guindo et al., 1994). Because N applied at the 4/5 LS to the delayed-flooded rice may have been subject to nitrification/denitrification losses due to alternate wetting and drying, the increased amount of N provided as a single application at the 4/5 LS ensured a greater amount of plant available N for uptake by the water-stressed plants. A midseason application of N to delayed flooded rice provided 50% less N to water-stressed plants during early vegetative growth, a critical time for N uptake to support rapid shoot and root development.

Table 2
The interaction of timing of floodwater application and draining on grain yield of three rice cultivars averaged over 1991 and 1992, experiment 2

Cultivars	Delayed flood (kg ha^{-1})		Normal flood (kg ha^{-1})	
	Early drain	Normal drain	Early drain	Normal drain
Alan	6420[a]	6220	5590	5900
Tebonnet	6290	6260	5940	6500
Texmont	5610	5550	5630	5580

[a] LSD (0.05) within a flood–drain combination=240; between flood–drain combinations=1890.

4. Conclusions

Results from two field studies conducted over four years revealed that there may be opportunities for reduced flood water inputs for rice production in southern USA. Results are comparable to studies conducted in other temperate rice-growing regions throughout the world. Full-season flush irrigation was not a satisfactory water management option for rice under flooded conditions in this region of USA. It would appear that the cultivars studied require the presence of a permanent flood during reproductive development and that the duration of the flood before and after that period can be altered without causing appreciable effects on grain yield and quality. Nitrogen applied as a single application at the four- to five-leaf stage resulted in greater N uptake by normal and delayed flooded rice compared to midseason applications of N, but did not result in higher yields.

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References

Beyrouty, C.A., Grigg, B.C., Norman, R.J., Wells, B.R., 1994. Nutrient uptake by rice in response to water management. J. Plant Nutr. 17, 39–55.

Beyrouty, C.A., Norman, R.J., Wells, B.R., Gbur, E.E., Grigg, B.C., Teo, Y.H., 1992. Water management and location effects on root and shoot growth of irrigated lowland rice. J. Plant Nutr. 15, 737–752.

Beyrouty, C.A., Wells, B.R., Norman, R.J., Marvel, J.N., Pillow, J.A., 1988. Root growth dynamics of a rice cultivar grown at two locations. Agron. J. 80, 1001–1004.

Bollich, P.K., Lindau, C.W., Norman, R.J., 1994. Management of fertiliser nitrogen in dry-seeded delayed flood rice. Aust. J. Exp. Agric. 34, 1007–1012.

Borrell, A., Garside, A., Fukai, S., 1997. Improving efficiency of water use for irrigated rice in a semi-arid tropical environment. Field Crops Res. 52, 231–248.

Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen-total. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties, 2nd Edition. American Society of Agronomy, Madison, WI, pp. 595–624.

Castillo, E.G., Buresh, R.J., Ingram, K.T., 1992. Lowland rice yield as affected by timing of water deficit and nitrogen fertilization. Agron. J. 84, 152–159.

Cooperative Extension Service, 1996. Rice Production Handbook. Univ. Ark. Coop. Ext. Ser. 192. University of Arkansas, Fayetteville, AR.

Counce, P.A., Siebenmorgen, T.J., Vories, E.D., Pitts, D.J., 1990. Time of draining and harvest effects on rice grain yield and quality. J. Prod. Agric. 3, 436–445.

De Datta, S.K., 1981. Principles and Practices of Rice Production. Wiley, New York.

Dingkuhn, M., Le Gal, P., 1996. Effect of drainage date on yield and dry matter partitioning in irrigated rice. Field Crops Res. 46, 117–126.

Guindo, D., Wells, B.R., Norman, R.J., 1994. Cultivar and nitrogen rate influence on nitrogen uptake and partitioning in rice. Soil Sci. Soc. Am. J. 58, 840–845.

Hefner, S.G., Tracy, P.W., 1991. The effect of nitrogen quantity and application timing on furrow-irrigated rice. J. Prod. Agric. 4, 541–546.

Lilley, J.M., Fukai, S., 1994. Effect of timing and severity of water deficit on four diverse rice cultivars. III. Phenological development. Field Crops Res. 37, 225–234.

McCauley, G.N., 1990. Sprinkler vs. flood irrigation in traditional rice production regions of south-east Texas. Agron. J. 82, 677–683.

McCauley, G.N., Turner, F.T., 1979. Rice production and water use efficiency in relation to flood period. In: Agronomy Abstracts. ASA, Madison, WI, p. 105.

Norman, R.J., Helms, R.S., Wells, B.R., 1992. Effect of delayed flood and nitrogen fertilization on dry seeded rice. Fert. Res. 32, 55–59.

Obermueller, A.J., Mikkelsen, D.S., 1974. Effects of water management and soil aggregation on the growth and nutrient uptake of rice. Agron. J. 66, 627–632.

Satyanarayana, T., Ghildyal, B.P., 1970. Influence of soil water regimes on growth and nutrient uptake by rice (*Oryza sativa*). Indian Soc. Soil Sci. J. 18, 51–55.

Slaton, N.A., Beyrouty, C.A., Wells, B.R., Norman, R.J., Gbur, E.E., 1990. Root growth and distribution of two short-season rice genotypes. Plant Soil 121, 260–278.

Tanaka, I., Nojima, K., Yoshimasa, U., 1963. Influence of drainage on the growth of rice plant in rice field. II. Relation between irrigation methods and the growth and yield of rice at various levels of nitrogen fertilization and sowing density. Proc. Crop Sci. Soc. Jpn. 32, 89–93 (in Japanese with English summary).

Tanaka, I., Nojima, K., Yoshimasa, U., 1964. Influence of drainage on the growth of rice plant in rice field. 3. The influence of irrigation management on the nutrient uptake, yield of rice plant and the mineral nitrogen content in soil. Proc. Crop Sci. Soc. Jpn. 33, 335–343.

Wells, B.R., Shockley, P.A., 1978. Response of rice to varying flood regimes on a silt loam soil. Il Riso. 27, 81–88.

Wilson Jr., C.E., Norman, R.J., Wells, B.R., 1989. Seasonal uptake patterns of fertilizer nitrogen applied in split applications to rice. Soil Sci. Soc. Am. J. 53, 1884–1887.

Yoshida, S., 1981. Fundamentals of Rice Crop Science. IRRI, Los Banos, Philippines.